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Finger flexion power generators made of piezoelectric lead zirconate titanate thin films on stainless steel foils

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ABSTRACT

We have fabricated flexible piezoelectric energy harvesters (PEHs) composed of $Pb(Zr,Ti)O_3$ (PZT) thin films on stainless steel foils and examined their power generation performance under a finger-bending motion for wearable applications. PZT thin films with a thickness of 3 μm were deposited on 30-μm-thick ferritic stainless steel (FSS) foils by RF magnetron sputtering, and the PEH elements were fabricated. Maximum effective output power of a single PZT thin-film PEH element reached 6 μW at 150 kΩ under the excitation of 2 m/s^2 at the resonance frequency of 11 Hz and the piezoelectric coefficient $e_{31,f}$ of the PZT thin films on the FSS foils was found to be −6.3 C/m^2. By connecting six PZT thin-film PEH elements, the output power of the stacked PEH increased to 13.4 μW at 300 kΩ. Because of small thickness of the PEH elements, the stacked PEH was flexible, and cracking or peeling of the PZT thin films did not occur during the continuous bending motion. The stacked PEH was embedded in gloves and light emitting diode (LED) lighting tests were conducted. By applying the finger-bending motions, we successfully turned the LED on intermittently using the generated electric power of the stacked PEH.

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1. Introduction

Recently, energy harvesters (EHs) have attracted considerable attention as potential power sources for microsensors, and a variety of these energy harvesting devices have been investigated for practical applications [1–4]. In particular, because vibration EHs (VEHs) directly convert mechanical energy to electrical energy even from human motions, their application to wearable sensor nodes is expected to expand the application of wearable products [5–7]. The power generation method of VEHs is typically categorized into three types: electrostatic, electromagnetic, and piezoelectric systems. Among these system types, piezoelectric energy harvesters (PEHs) have several advantages for use in wearable devices, such as a simple structure and excellent power conversion efficiency from mechanical energy to electrical energy [4,8,9].

Considering the application of PEHs in wearable devices, electric power should be extracted from human motions as they have lower frequency but higher mechanical power input than that of typical environmental vibrations. This indicates that the operating conditions are different from conventional PEHs. A typical application of wearable PEHs is a shoe-mounted power generator [5,10,11]. In our previous study, we fabricated shoe-mounted PEHs using $Pb(Zr,Ti)O_3$ (PZT) thick-film bimorph cantilevers and demonstrated the bluetooth low energy (BLE) transmission of the foot pressure data using the PEH generated power [11]. When PEHs are installed in the clothes, wearable battery-free sensor devices can be realized [12,13]. This is especially true for the bending motion of body joints as it generates large mechanical power. If the large mechanical power can be converted to electrical energy using a PEH, a relatively large amount of electric power can be supplied to wearable sensors. Despite the large output power, wearable PEHs must be highly flexible and light-weight. Therefore, piezoelectric polymers such as polyvinylidene fluoride (PVDF) have been extensively used as flexible and soft EHs [14,15]; however, these EHs still show insufficient output performance because of their lower piezoelectric coefficient compared with PZT. Instead of using such abovementioned piezoelectric polymers, we deposited PZT thin films on stainless steel (SS) foils by RF magnetron sputtering and confirmed their reliability [16–18]. As a result, highly flexible ferroelectric PZT thin films were achieved. In addition, PEHs made using PZT thin films on SS foils are flexible and light-weight, with potential to replace PEHs containing piezoelectric polymers [17–20]. Recently, Yeo et al. reported PZT thin-film energy harvesters for wearable applications using PZT thin-film bimorphs deposited on both sides of Ni foils [20]. Electric power was produced by magnetic plucking force during swing-arm motion. However, both-side deposition of the PZT

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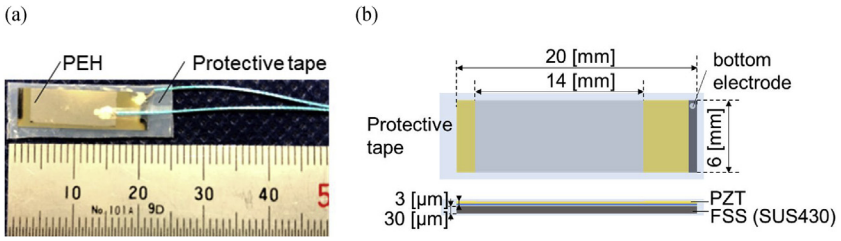

Fig. 1. Structure of the PZT thin-film energy-harvesting element; (a) optical photograph and (b) schematic of the surface and cross-sectional structure.

thin films for bimorph structure would be a troublesome process because different thermal history of two PZT layers would cause different qualities of the PZT thin films.

In this study, we fabricated PEH-embedded gloves and generated electric power through finger-bending motions. The PEHs were composed of PZT thin films deposited on 30-μm-thick SS foils. The fabrication process of unimorph PZT thin-film PEHs is simpler than that of bimorph PEHs and stable power generation can be expected even under large bending deformation. To increase output power, we used the six-elements stacked PEHs and measured their output power during the finger-bending motions.

2. Fabrication of PZT thin-film piezoelectric energy harvesting elements

PZT thin films were deposited on 30-μm-thick ferritic stainless steel (FSS) foils by RF magnetron sputtering [16–18]. Before the PZT deposition, we deposited Pt/Ti on FSS foils as bottom electrodes and then (Pb,La)TiO_3 (PLT) seed layers were deposited at the interface of the PZT and Pt/Ti-deposited FSS foils to promote the crystal growth of the PZT [21]. PZT thin films of 3 μm in thickness were deposited on the FSS foils at a substrate temperature of approximately 600 °C.

After the deposition of the thin films, post-annealing was conducted for 1 h at 650 °C to ensure the crystallization of the perovskite structure. Finally, Pt-top electrodes were deposited on the PZT thin films using a shadow mask, and the PZT thin-film PEH elements' fabrication was complete. The elements displayed high toughness and flexibility owing to the small thickness of the FSS foils and excellent adhesion of the foils with the PZT thin films. Fig. 1 shows an optical photograph and schematic of the PZT thin-film PEH elements. The length and width of the PEH elements were 20 and 6 mm, respectively. The surface of the PEH elements were coated with an insulating fluorine tape (ASF-110, Chukoh Chemical Industries, Ltd.), of which the surface was very smooth, with a low amount of friction, such that each PEH element could bend freely. In this study, we attached the PZT thin-film PEH elements on the fingers of a glove and attempted to scavenge electric power via finger motions while wearing the glove. To increase the electric power, we used six PEH elements; series-connected double EH elements were overlapped, and three of them were connected in parallel.

3. Crystal structure and electric properties of PZT thin films

We evaluated the crystal structure of the PZT thin films on the FSS foils by X-ray diffraction (XRD). The XRD patterns are shown in Fig. 2(a). The XRD measurements indicated that polycrystalline PZT thin films with perovskite structure were prepared on the FSS foils. Surface morphology of the PZT thin films is observed by scanning electron microscopy (SEM) and a SEM image of the surface is shown in Fig. 2(b). We observed a dense and pinhole-free PZT thin-film surface structure on the top of the FSS foils.

Table 1
Electrical properties of the PZT thin-film piezoelectric energy harvester element.

PZT thickness [μm]	3.0
Electrode area [mm^2]	84
Capacitance [nF]	96.5–118.9
Relative dielectric constant (ε_r)	389–480
Dielectric loss (tanδ) [%]	4.5–6.8

The dielectric properties of the PZT thin films on the FSS foils were measured using an LCR meter (NF, ZN2353), and the results are shown in Table 1. The relative dielectric constant was around 400, which is lower than that of PZT thin films on Si substrates but similar to PZT on metal substrates [16–18]. The low relative dielectric constant was attributed to a large compressive stress due to the difference of the PZT and FSS thermal expansion coefficients during the cooling process that occurred after the high-temperature sputtering deposition of the PZT thin films [16–21]. Dielectric loss was less than 7 %, indicating that leakage current in the PZT thin films is sufficiently low for its use as an EH material.

4. Power generation of piezoelectric energy harvesters

4.1. Basic power generation performance of PZT thin-film PEHs

To evaluate the basic power generation characteristics of the PZT thin-film PEH elements, output power was measured using a vibration exciter (512-A, EMIC). Fig. 3 shows a schematic and photograph of the measurement system. The PZT thin-film PEH element was clamped using a fixture to create a cantilever configuration. The tip mass was attached on the other end of the PEH element as shown in Fig. 3(b). The measurement was performed at the resonance frequency (11 Hz) of the PEH and at an acceleration of 2 m/s^2. Output voltage between a load resistance was measured using an oscilloscope. Fig. 4 shows the output voltage as a function of the load resistance. The output voltage produced by the piezoelectrics was measured across a load resistance without any other circuit such as a rectifier, and the effective output power P was derived using the following equation,

$$P = \frac{(V_{rms})^2}{R} \tag{1}$$

where V_{rms} and R are the root-mean-square voltage and load resistance, respectively. Theoretical output voltage and power are plotted in Fig. 4. This plot indicates that the experimental values of electric power generation were in good agreement with those of the theoretical calculation. The open circuit voltage was 1.35 V, whereas, the maximum output power P reached 6 μW at 150 kΩ. The direct piezoelectric coefficient $e_{31,f}$ of the PZT thin films can be calculated using the open circuit output voltage V_{out} and tip displacement δ_{in}. The equation used for this calculation is as follows [22],

$$e_{31,f} = -\frac{4l^3}{3wh_s(1-\nu_s)(x_1-x_0)(2l-x_1-x_0)} \cdot \frac{Q_{out}}{\delta_{in}} \tag{2}$$

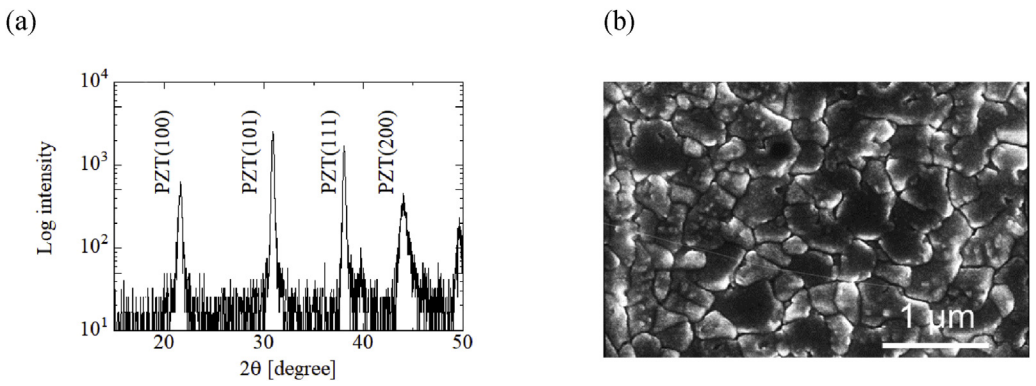

Fig. 2. Crystal structure and surface morphology of PZT thin films on 30-μm-thick FSS foils using (a) XRD patterns and (b) a surface SEM image, respectively.

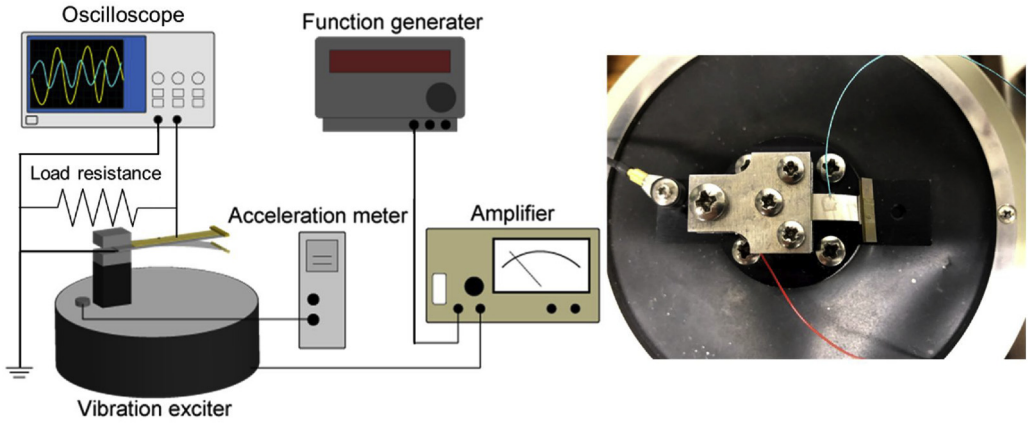

Fig. 3. Schematic (left) and an optical photograph (right) of the measurement systems used to determine the output power of the single PZT thin-film PEH element.

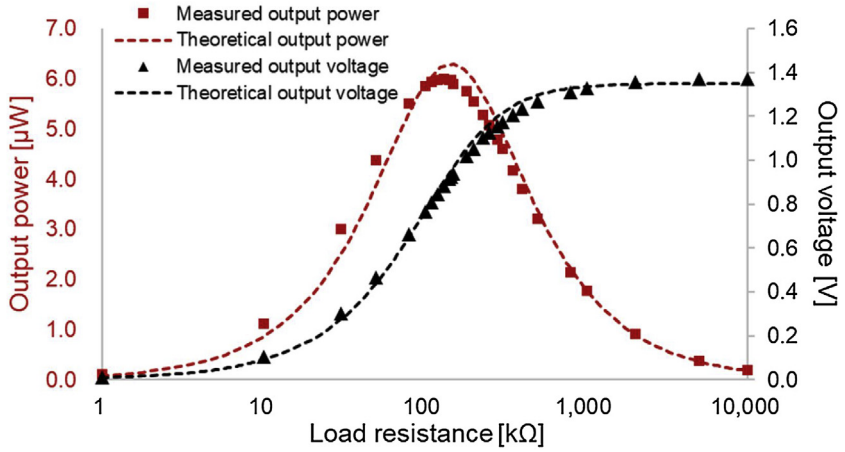

Fig. 4. Output voltage and power of a single PZT thin-film PEH element as a function of load resistance. The measurements were performed at the resonance frequency of 11 Hz and an acceleration of 2 m/s^2. Measured (square and triangle points) and theoretical (dashed line) values are plotted.

where l, w, h_s, ν_s, and Q_{out} are the length, width, thickness, Poisson's ratio of the substrate, and output electrical charge, respectively, of the PEH cantilever. The value obtained for the piezoelectric coefficient $e_{31,f}$ was -6.3 C/m^2. This value was almost same as the direct piezoelectric coefficient e_{31_f} of polycrystalline PZT thin films on Si [22]. However, the piezoelectric properties strongly depend on the density, orientation and morphotropic phase boundar (MPB) composition of the PZT thin films [23], and the further improvement would be expected by the intensive optimization of the structure and composition of the PZT thin films on FSS foils.

4.2. Power generation through finger-motions

To increase output power, stacked PEHs were fabricated by connecting six PZT thin-film PEH elements and their power supply capability was tested using a light emitting diode (LED). A schematic and a photograph of the PZT thin-film PEHs are shown in Fig. 5. The stacked PEHs consisted of six PZT thin-film PEH elements; two single elements were connected in series, and three of the elements were connected in parallel after attaching to three fingers as shown in Fig. 5(a). The stacked PEHs were flexible and bent easily without any extra force because the total thickness of

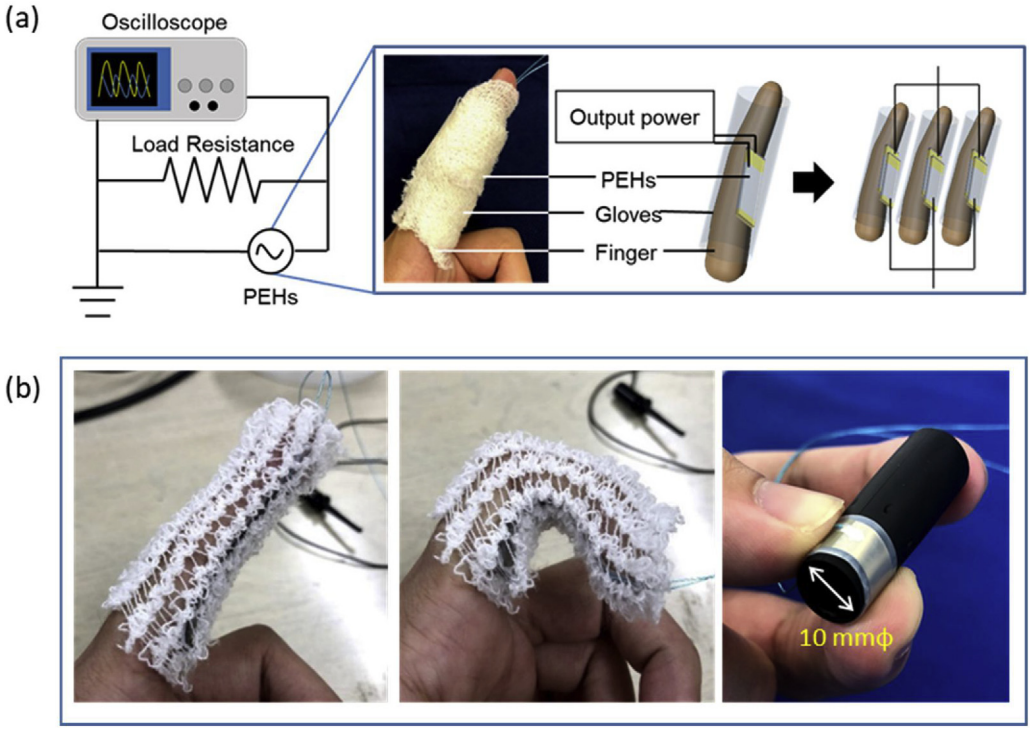

Fig. 5. Schematic of the measurement system and flexion bending deformation of the PEH; (a) measurement setup and structure of the finger-bending power generator fabricated using stacked PZT thin-film PEHs and (b) photo images of finger-bending deformation of the PEHs.

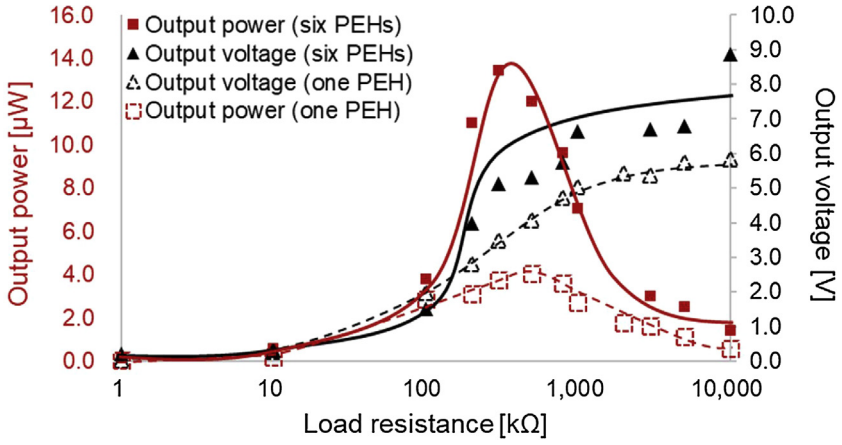

Fig. 6. Load resistance dependence of output voltage and power for the stacked PZT thin-film PEH composed of single and six elements.

the FSS foils was 60 μm. In addition, adhesion of the foils to the PZT thin films was strong even at large bending deformations and stable electric power could be generated via a finger flexion motion.

Fig. 5(b) shows the pictures of the finger flexion and bended PEH element. In this experiment, the typical the radius of curvature (R_c) of the bending deformation was of 5 mm, and the applied stress to the 3-μm-thick PZT thin films on 30-μm-thick FSS was calculated as 254 MPa by the following equation:

$$\sigma = E_{PZT}\frac{y}{R_c} \tag{3}$$

where E_{PZT}, and y are Young's modulus of PZT (73 GPa) and distance from neutral plane of PZT/FSS (17.4 μm), respectively. This result indicates that the applied stress by typical finger flexion motions is lower than the fracture stress of the PZT thin films on Si reported by K. Coleman [24]. We confirmed the PZT thin films generated electric power stably by both compressive and tensile bending deformation without cracking or peeling of the PZT thin films.

Fig. 6 shows the output voltage and power of the single and stacked PEHs during the finger flexion motions. For a single PEH element, the open circuit voltage reached 5.8 V, and maximum output power P was 2.5 μW at 500 kΩ. On the other hand, the open circuit voltage of the stacked PEHs reached 9.4 V, and maximum output power P was 13.4 μW at 300 kΩ, which is a 5.4 times larger output power than that of a single PEH element. These results indicate that the output power can be increased by stacking the PEH elements.

Assuming possible wearable applications of the stacked PEHs, we attempted LED lighting tests via the finger flexion motions. Fig. 7 shows a schematic of the LED switching circuit. The stacked PEH elements were connected to the energy harvesting module (LTC3588-1), and the LED (KP-OSW4DK2) turned on when the capacitor was charged. Fig. 7(b) is an optical image of the lit (turned

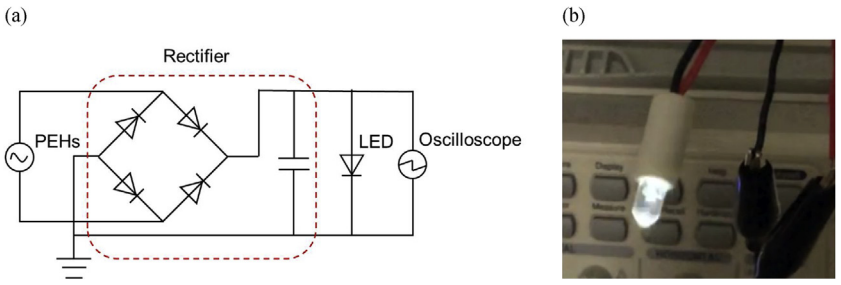

Fig. 7. Demonstration of LED lighting by a flexible PZT thin-film PEH—(a) schematic of an LED powered by a PEH and (b) photograph of the lit (turned on) LED.

on) LED. In this experiment, we successfully lit the LED intermittently by the finger flexion of the PEHs. At the current stage, we were not able to continuously turn on the LED owing to a slight lack of output power. However, a stable power supply for continuous lighting of the LED would be possible by increasing the number of PEH elements. Charging the electric power to batteries, even when the PEH element is not in use, is also a practical method for the power generator to supply electric power to wearable devices such as sensors, which are usually operated intermittently. In this study, we fabricated flexible PZT thin-film PEHs and successfully demonstrated the lighting of a LED. We believe that this achievement will expand the area of application of PEHs as power sources of practical wearable devices.

5. Conclusion

In this study, we fabricated PEHs that were embedded in gloves to generate electric power via finger-bending motions. The PEHs were composed of PZT thin films deposited on 30-μm-thick FSS foils using RF magnetron sputtering. The PZT thin-film PEH elements were tough and flexible owing to the small thickness of the FSS foils and excellent adhesion of the foils with the PZT thin films. The effective output power P of the single PZT thin-film PEH elements reached 6 μW at 150 kΩ under the excitation of 2 m/s^2 at the resonance frequency of 11 Hz, and a piezoelectric coefficient $e_{31,f}$ of -6.3 C/m^2 was obtained. Series and parallel connections of six PZT thin-film PEH elements enabled an increase in the total output power. The output power P of the stacked PEHs was 13.4 μW at 300 kΩ, which is a 5.4 times larger output power than a single PEH element. Using the stacked PEHs, we successfully and intermittently turned on an LED via finger flexion. We believe our results will expand the use of PEHs as power sources for practical wearable devices.

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CRediT authorship contribution statement

Ryo Harada: Methodology, Formal analysis, Investigation, Resources, Writing - original draft. **Naoya Iwamoto:** Methodology, Formal analysis, Investigation. **Sang-Hyo Kweon:** Methodology, Validation. **Toshihito Umegaki:** Methodology, Validation. **Isaku Kanno:** Conceptualization, Methodology, Investigation, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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